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Torque-luminosity correlation and possible evidence for core-crust relaxation in the X-ray pulsar GX 1+4

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Abstract. We present the detection of a positive correlation between spin-down rate \dot{P} and pulsed X-ray luminosity in the BATSE archival data of the bright hard X-ray pulsar GX 1+4. We have also seen a delay of 5.6 ± 1.2 days between the luminosity change and the corresponding change in the spin-down rate. The observed correlation between \dot{P} and L_X is used to reproduce the period history of GX 1+4 based on the observed luminosity alone, and it is found that the spin period can be predicted correct to 0.026% when the luminosity is adequately sampled. The idea that at a higher luminosity more matter is accreted and the accretion disk extends closer to the neutron star thereby transferring more angular momentum to the system, seems not to be the case with GX 1+4. The observed lag between the spin-down rate and the luminosity is reported here for the first time in any such binary X-ray pulsar, and is found to be consistent with the time scale for the core-crust relaxation in a neutron star.

Key words: X-rays: stars - pulsars: individual - GX 1+4

1. Introduction

Period variations in X-ray binary pulsars are quite common and a number of pulsars show both spin-down and spin-up episodes over time scale of years or less. In binary systems with Roche-lobe overflow of the mass losing secondary, such variations are generally explained in terms of the conventional accretion disk theory where the spinning-up or spinning-down of a neutron star of a given magnetic moment, mass and period depends only on the X-ray luminosity. In binary systems containing massive early type secondaries, however, accretion onto the neutron star is mostly through strong stellar wind and conditions for forming stable accretion disks are generally not present. According to the numerical simulations of mass accretion

onto such systems (Taam & Fryxell 1988; Blondin et al. 1990; Matsuda et al. 1991) the small accreted specific angular momentum can change sign in an erratic manner which may lead to alternating spin-up and spin-down episodes. Study of torque-luminosity relationships in X-ray binary systems can therefore, be very instructive in understanding the accretion process in them.

The luminous hard X-ray pulsar GX 1+4, first detected in 1970 (Lewin et al. 1971), has several characteristics which makes it an ideal source to test out the concepts of accretion powered X-ray pulsars. It has shown a continuous decrease of pulse period (spin-up) from about 135s in 1970 to about 110s in 1980 and it was included as one of the test sources in understanding the behaviors of disk-fed X-ray pulsars (Ghosh & Lamb 1979a,b). The source was below the detection limit of EXOSAT in 1983 (Hall & Davelaar 1983) and after its rediscovery by GINGA in 1987 (Makishima et al. 1988) it has been showing a monotonically increasing spin period (spin-down), except for a brief spin-up episode in between (Finger et al. 1993; Chakrabarty et al. 1994). GX 1+4 has been identified with a red giant M6III star V2116 Oph having an emission line spectrum that resembles a symbiotic star with a strong stellar wind (Davidsen et al. 1976). So far no binary period has been detected from this system, although optical pulsations with the same period as in X-rays have recently been reported (Jablowski et al. 1996). The presence of a giant companion and period change sign reversals could imply that GX 1+4 is a wind-fed system without a stable accretion disk. A correlation between spin-down and X-ray luminosity was pointed out by Chakrabarty (1996), which is in apparent contradiction with the general ideas of X-ray pulsars with accretion disks. To confirm the correlation between spin-down and X-ray luminosity found by Chakrabarty (1996) and to understand the torque-luminosity relation in greater detail, we have obtained the pulse period and luminosity history of GX 1+4 for about 1200 days from the Compton Gamma Ray Observatory Science Support Center (COSSC) BATSE archive

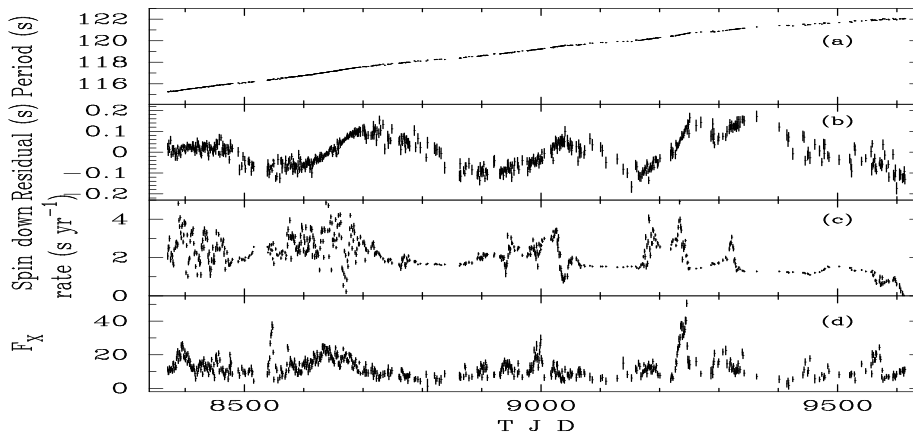


Fig. 1. The pulse period and the pulsed flux history of GX 1+4 obtained from the BATSE archive. The ordinate is time in Truncated Julian Days (TJD). a) The pulse period b) a best fit quadratic function subtracted from the period data to show the few hundred days features, c) the instantaneous spin down rate \dot{P} (see text) and d) The observed pulsed flux F_X at 40 keV (10^{-5} photons $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$).

and carried out our analysis. In the following sections, we present the analysis, results and its implications.

2. Data

The pulse period and the luminosity of GX 1+4 for Truncated Julian Day (TJD) 8370 to 9615 (ie., 1991 April 24 to 1994 September 20) were obtained from the COSSC archive. The observations were done with BATSE Large Area Detectors (see Fishman et al. 1989 for a description of BATSE). The archived data consists of the pulsar frequency obtained from blind searches and epoch folding performed on the BATSE data, the confidence level of the period determination and a Y/N flag indicating whether the confidence level exceeds a predetermined value. The archive also provides the pulsed flux F_X at 40 keV obtained by fitting an optically thin thermal bremsstrahlung (OTTB) spectrum of temperature 50 keV for channels 1 to 5 (25 to 98 keV). In the following analysis, we have taken only those data points with flag Y (i.e., the period determination is reliable), unless otherwise mentioned.

3. Analysis and results

The pulse period and the observed pulsed flux F_X at 40 keV are plotted in Fig. 1 for TJD 8350 – 9650 (Fig. 1a and 1d, respectively). A linear fit to the pulse period gives an average value for \dot{P} of 2.12 s yr^{-1} . A quadratic fit to the data gives a value of $\dot{\nu}/\nu$ of 8.3 yr. Higher order polynomials do not improve the fit. To see the period variation in more detail, the residuals to the quadratic fit are shown in Fig. 1b. The pulsed X-ray flux is seen to increase by a factor of ≥ 4 for duration of 2 – 10 days compared to the average flux and by a factor of ≥ 2 for a duration of about 20 – 100 days. Since F_X is obtained after fitting a OTTB spectrum, it is in fact a measure of the hard X-ray pulsed

luminosity. Though there have been some indications of an anti-correlation between pulse fraction and total X-ray luminosity (Rao et al. 1994), the observed pulse fraction in the present spin-down era lies in a narrow range of 0.3 to 0.5. In fact, from a compilation of hard X-ray luminosity of GX 1+4 (Chitnis 1994) we find a positive correlation between X-ray luminosity and F_X . Hence, in the following, we treat F_X as a measure of the total X-ray luminosity.

To examine whether the luminosity is related to the pulse period variation, the instantaneous spin down rate \dot{P} is calculated for each of the data points by doing a linear fit to the neighboring 25 data points and this is shown in Fig. 1c. The similarity in the Figs. 1c and 1d led to further analysis of correlation and cross-correlation between \dot{P} and the pulsed flux F_X .

3.1. Spin down rate and luminosity

To estimate the correlation of spin change rate and luminosity we choose only those \dot{P} values where the linear fit around that data point (for about ± 12 days) is acceptable (unlike Fig. 1c. where all the data points are included). As the regions of very high F_X are of short durations, the determination of \dot{P} is not very reliable and hence we exclude those points from our analysis. The two quantities are positively correlated and we have calculated a correlation coefficient of 0.63 (for 102 data points) and the probability of no correlation in the given data set is estimated to be 10^{-12} .

To investigate whether the pulse period variation is completely governed by the luminosity variation, we made an attempt to reproduce the pulse period history of GX 1+4 only from the luminosity history. The positive correlation seen between \dot{P} and F_X is assumed to be the real torque transfer equation in the pulsar and the pulse period of the first data point is propagated with time depending

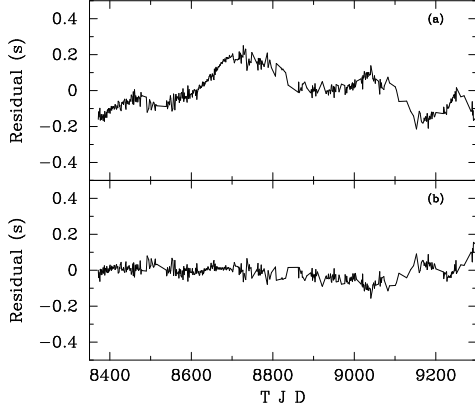


Fig. 2. Residuals of pulse period plotted versus time in TJD. a) The 100-200 days features in the observed period when a linear fit is subtracted. b) The coefficients for a best fitted straight line between \dot{P} and F_X is used to reproduce the pulse period of GX 1+4, only taking pulsed luminosity into consideration and the difference of the observed and calculated period is shown here.

on F_X , using the linear relation obtained between \dot{P} and F_X . For this purpose we have used those F_X values even when the period determination is uncertain (Flag N in the archive). The resultant residuals in the period determination are shown in Fig. 2b. For comparison, we show in Fig. 2(a) the residuals to the period obtained by assuming a constant \dot{P} . The 100 – 200 days features in the upper plot is not present in the lower plot signifying that the pulse period changes are actually correlated to the luminosity. However, the reproduction of the pulse period for days later than TJD 9000 deviates from the observed one by up to about 0.5 s because of the lack of sufficient number of F_X measurements. The rms deviation in the pulse period as estimated from only a constant \dot{P} (Fig. 2a) is 0.1 s and it improves to 0.04 s when pulse period is predicted from the $\dot{P} - L_X$ relation (Fig. 2b). The rms deviation reduced further to 0.03 s (which is the typical error in the period determination) for TJD 8370 to 9000 (where F_X is well determined and well sampled). Hence, we can conclude that when F_X is well sampled, all the variations in period can be explained correctly within the observational errors using a simple linear relation between \dot{P} and F_X .

3.2. Time delay

The instantaneous spin-down rate and the pulsed flux were subjected to cross-correlation tests. For this purpose \dot{P} is calculated using two neighboring data points and the average value of F_X is used. When the total data is taken we find a positive correlation between \dot{P} and F_X at a confidence level of 99.4%. The reduced level of confidence is due to the fact that \dot{P} is calculated over 2 observations (unlike ± 12 data points used in the previous section). The correlation, however, was found to be delayed by a few

days. To improve the confidence level, the total data are divided into several sets of 128 data points and the derived cross-correlation values are co-added. The resultant profile is shown in Fig. 3. The central part of the figure is shown in an expanded form in the inset to the figure. As can be seen from the figure, there is a clear asymmetry near 0. A Gaussian fit to the profile near 0 gives a χ^2 of 20 for 35 degrees of freedom (dof) and the derived value of delay is $(4.8 \pm 1.0) \times 10^5$ s (5.6 ± 1.2 days). The errors are calculated by the criterion of $\chi^2_{min} + 2.3$ (1σ error for two free parameters). A constant fit to the profile gives $\chi^2 = 75$ for 36 dof showing the existence of correlation at a confidence level of 99.99%. This confidence level improves further if the value of the constant is kept fixed at 0 (i.e., there is no correlation instead of constant correlation). A Gaussian fit with the centroid frozen at zero gives $\chi^2 = 54$ signifying the existence of a delay at a very high confidence level (the value of $\Delta\chi^2$ being 34 for one additional parameter). Hence the co-adding method resulted in the detection of a delay at a high confidence level, and could be the reason for the lack of detection of any such delay by other workers (Chakrabarty 1996). The delay between \dot{P} and F_X is seen for the first time in an X-ray pulsar.

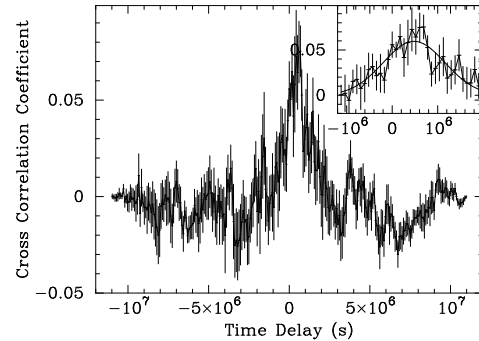


Fig. 3. The cross correlation between \dot{P} and F_X is plotted here. Inset gives expanded view for the central part of the plot. The asymmetry seen here corresponds to 5.6 ± 1.2 day delay for \dot{P} compared to F_X .

4. Discussion

The frequent and large variations in the X-ray luminosity of GX 1+4 observed with BATSE are quite similar to those found in the other accretion-powered X-ray pulsars. Power spectrum analysis of the luminosity fluctuations shows a power-law component (index = -2.1) indicative of a red noise in the system and has been seen before (Baykal & Ogelman 1993). Power spectrum analysis of the period fluctuations also shows a red-noise component. Period fluctuations have also been seen in other accreting pulsars with time scales down to a few days, but the red noise component seen here suggests that these fluctuations

might represent torques that are internal to the neutron star rather than due to inhomogeneities in the accretion flow (White et al. 1995). The luminosity fluctuations are found to be correlated with the instantaneous \dot{P} , which always stays positive throughout the observation. The direct positive correlation of \dot{P} with the X-ray luminosity is difficult to explain in terms of accretion disk models (Ghosh & Lamb 1991) as in such models an increase in luminosity is related to increased mass accretion rate that decreases the inner radius of the disk and leads to a spin-up of the neutron star i.e., negative \dot{P} . On the other hand, if GX 1+4 accretes matter directly through stellar wind with negligible specific angular momentum, then the reversal of spin change sign could mean a reversal in the direction of the small disk that can form. A positive correlation between \dot{P} and L_X can then be expected, as a sudden decrease in the net angular momentum can lead to an increase in accretion (King 1995).

The delay between L_X and \dot{P} is difficult to explain in any accretion theory. The region of hard X-ray emission is very close to the neutron star surface and one cannot expect any delay between the X-ray emission and the resultant angular momentum transfer to the neutron star. Hence we look for some phenomena internal to the neutron star as a possible explanation to the delay. In this regard it is very instructive to compare these results to a similar phenomena observed in GRO J1744-28 (Stark et al. 1996). Stark et al. have found a phase lag in the bursting X-ray pulsar GRO J1744-28. During an X-ray burst when the X-ray luminosity increased by more than a factor of 15 in about 10 s, the phase lag increased to about 28 ms and subsequently the phase lag relaxes back with an exponential decay time of about 720 s. Interpreting this phenomenon in terms of models for pulsar glitches developed for radio pulsars, the phase lag during the burst corresponds to an initial spin-down with $\Delta\Omega/\Omega \sim -10^{-3}$. The exponential decay time scale is equated to the crust-core coupling time scale, which is $(4 \times 10^2 - 10^4) P$, where P is the rotation period of the neutron star (Alpar & Sauls 1988). If the phenomena observed in GRO J1744-28 is treated as an impulse response to luminosity change and if this phenomena is common to GX 1+4 too, continuous changes in luminosity (as seen in GX 1+4) will reflect as a delay in the \dot{P} variation. The magnitude of period variation in GX 1+4 ($dP/P = -\Delta\Omega/\Omega \sim 10^{-3}$) is comparable to that seen in GRO J1744-28. Further, the observed time scale (6 days) agrees with the relation between τ and P given by Alpar & Sauls (1988).

The observed lag of \dot{P} with respect to L_X is, therefore, consistent with the impulse response of X-ray luminosity variation seen in GRO J1744-28, with the time scales scaled up according to the relation given for core-crust relaxation. As pointed out by Stark et al., for the core-crust relaxation to occur, first the crust has to decouple and the angular momentum has to be transferred to the crust and

the crust couples back to the core in a time scale given by Alpar & Sauls.

In conclusion, our analysis of the period and X-ray luminosity history of GX 1+4 observed with the BATSE shows: (i) a positive correlation between pulsed hard X-ray luminosity and spin-down rate, and (ii) the spin-down rate lags by 5.6 ± 1.2 days with respect to the pulsed luminosity. These results suggest that the internal torque of the neutron star can play a dominant role in the period-luminosity history of GX 1+4.

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